NSF *NCAR* | NASA *GSFC* | DOE *LANL ANL* | NOAA *NCEP GFDL* | MIT | U MICH

The Earth System Modeling Framework

ESMF

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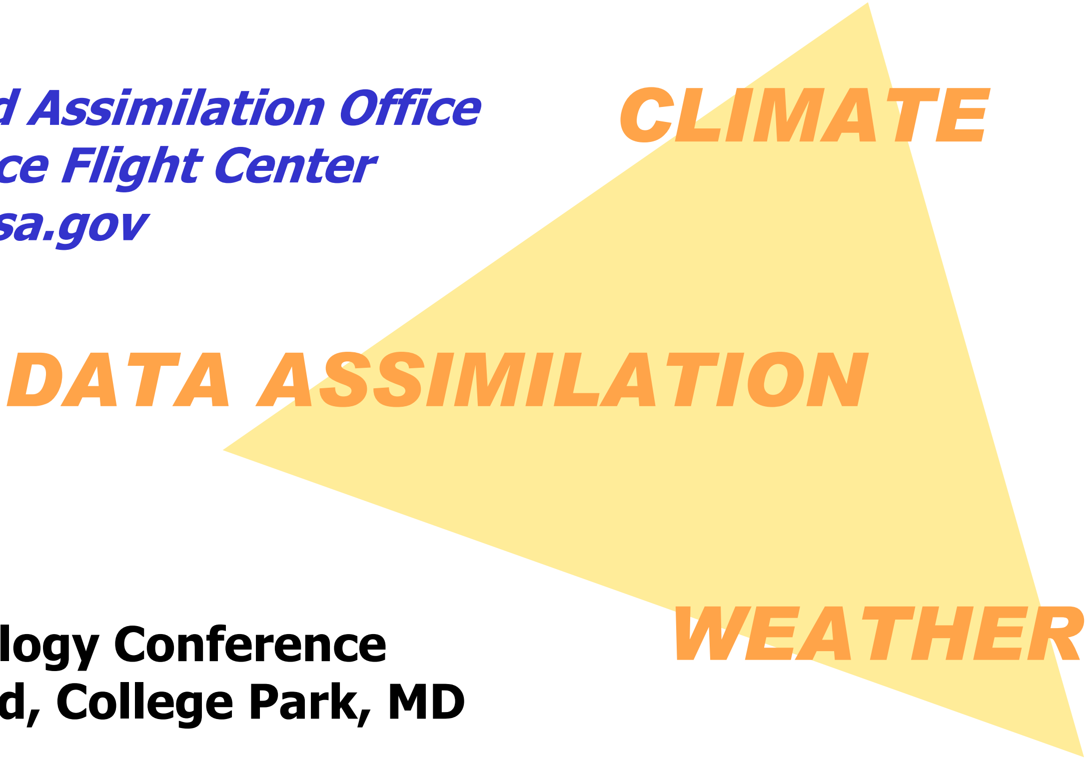

Earth Science Technology Conference
University of Maryland, College Park, MD
25 June 2003

www.esmf.ucar.edu

ESMF

Outline

1. Introduction
2. Project Overview
3. Timeline and Status
4. Deployment Activities
5. ESMF Design Principles
6. ESMF Architecture
7. ESMF Demo
8. Adopting ESMF
9. Summary

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Technological Trends

In climate research and NWP…

increased emphasis on detailed representation of individual physical processes; requires many teams of specialists to contribute components to an overall coupled system

In computing technology…

increase in hardware and software complexity in high-performance computing, as we shift toward the use of scalable computing architectures

Community Response

- **Modernization of modeling software**

  Abstraction of underlying hardware to provide uniform programming model across vector, uniprocessor and scalable architectures

  Distributed development model characterized by many contributing authors; use of high-level language features for abstraction to facilitate development process

  Modular design for interchangeable dynamical cores and physical parameterizations, development of community-wide standards for components

- **Development of prototype frameworks**

  GFDL (FMS), NASA/GSFC (GEMS), NCAR/NCEP (WRF), NCAR/DOE (MCT), etc.

The ESMF aims to unify and extend these efforts

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Project Overview

GOAL: To increase software reuse, interoperability, ease of use and performance portability in climate, weather, and data assimilation applications

PRODUCTS:

- Coupling superstructure and utility infrastructure software
- Synthetic code suite for validation and demonstration
- Set of 15 ESMF-compliant applications (including CCSM, WRF, GFDL models, MIT, NCEP and NASA data assimilation systems)
- Set of 8 interoperability experiments

RESOURCES: $10M over 3 years

The ESMF Team

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Teams and PIs:	Part I: Core ESMF Development (Killeen, NCAR) Part II: Modeling Applications (Marshall, MIT) Part III: Data Assimilation Applications (da Silva, NASA DAO)
Core Technical Leads:	V. Balaji/GFDL, Cecelia DeLuca/NCAR, Chris Hill/MIT
Co-Investigators:	NASA/GSFC-DAO, NASA/GSFC-NSIPP, DOE/LANL, DOE/ANL, University of Michigan, MIT, NSF/NCAR-SCD, NSF/NCAR-CGD, NSF/NCAR-MMM, NOAA/NCEP, NOAA/GFDL
Term:	3 years, starting February 2002

Organization

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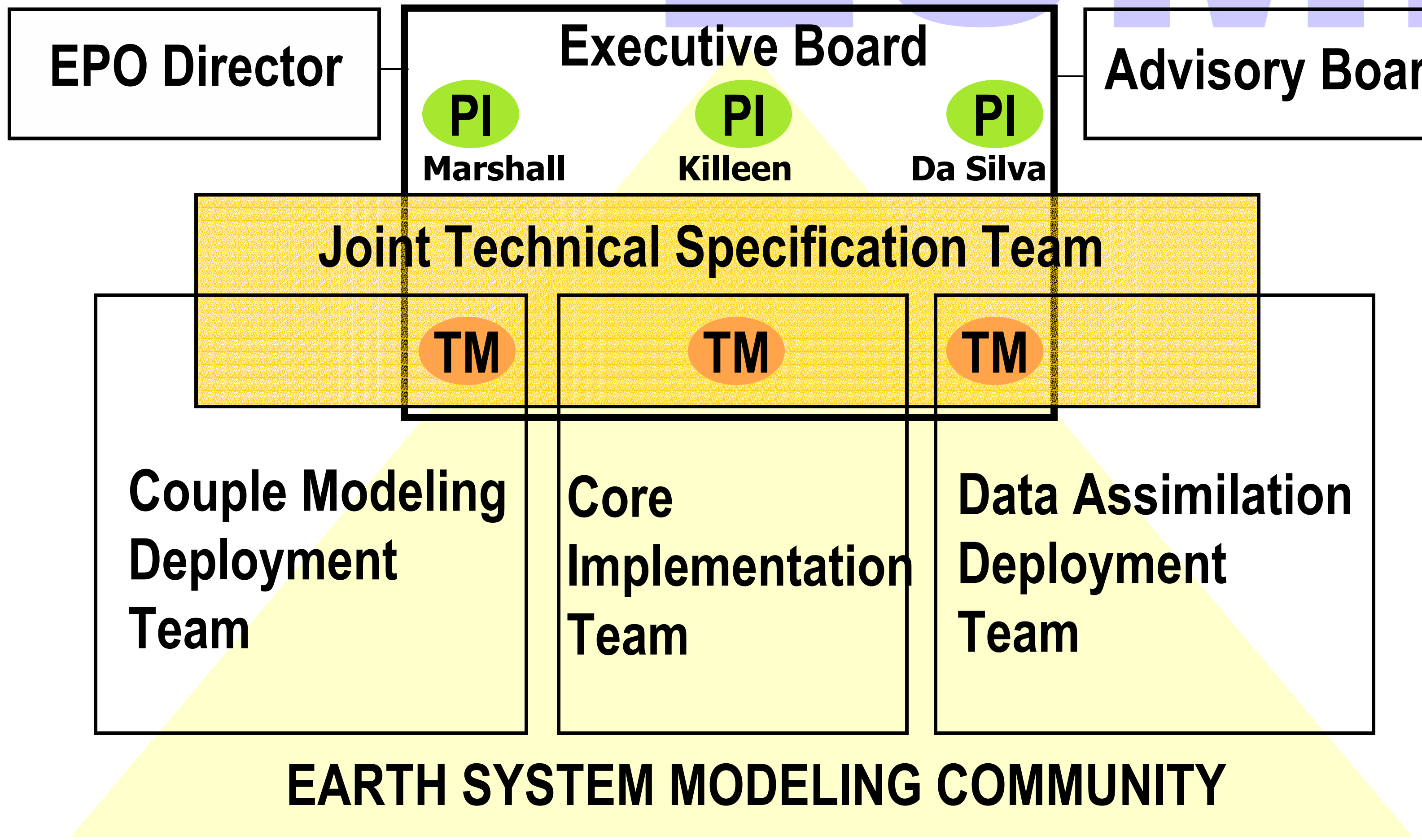

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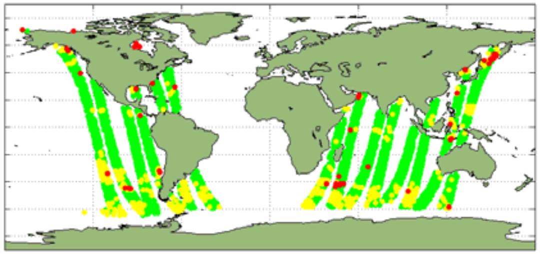
Timeline and Status

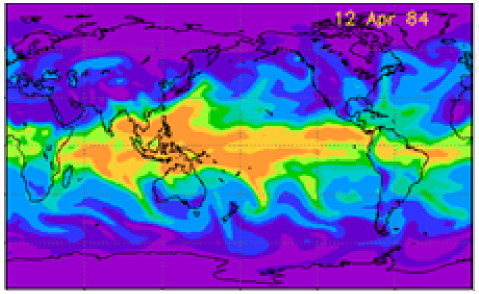
Feb 2002	Funding started
May 2002	Draft Developer's Guide and Requirements Document completed
	Community Requirements Meeting and review held in D.C.
July 2002	ESMF VAlidation (EVA) suite assembled
August 2002	Architecture Document: major classes and their relationships
	Implementation Report: language strategy
	Software Build and Test Plan: sequencing and validation
April 2003	First API and software release with Community Meeting review
Fall 2003	First interoperability experiments completed
April 2004	Second API and software release with Community Meeting review
July 2004	Interoperability experiments completed

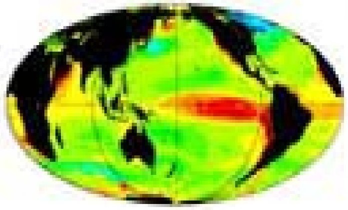
Deployment Activities



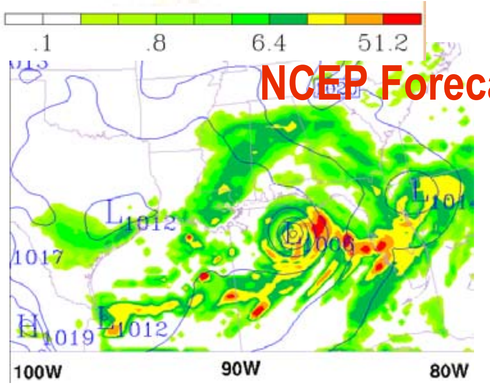
NASA GSFC PSAS

GFDL FMS Suite

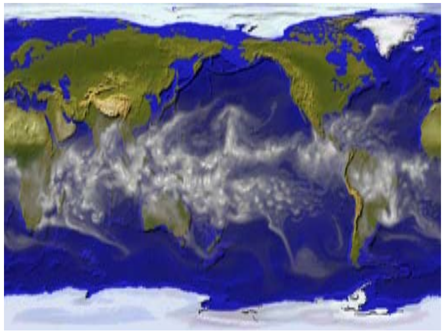




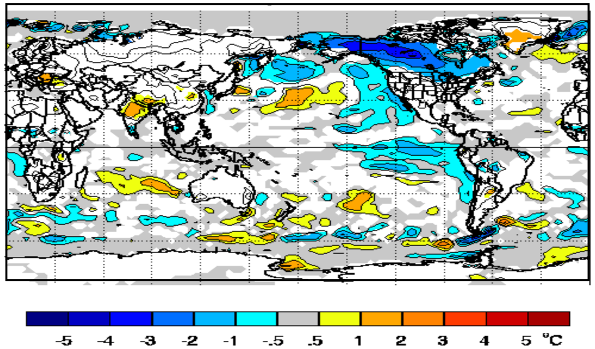
MITgcm



NCEP Forecast



NCAR/LANL CCSM



NSIPP Seasonal Forecast

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Coupled Modeling Codes

GFDL

- h FMS B-grid atmosphere at N45L18
- i FMS spectral atmosphere at T63L18
- j FMS MOM4 ocean model at 2°x2°xL40
- k FMS HIM isopycnal C-language ocean model at 1/6°x1/6°L22

MIT

- l_c MITgcm coupled atmosphere/ocean at 2.8°x2.8°, atmosphere L5, ocean L15
- m MITgcm regional and global ocean at 15kmL30

NSIPP

- n_c NSIPP atmospheric GCM at 2°x2.5°xL34 coupled with NSIPP ocean GCM at 2/3°x1.25°L20

NCAR/LANL

- o_c CCSM2 including CAM with Eulerian spectral dynamics and CLM at T42L26 coupled with POP ocean and data ice model at 1°x1°L40

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Data Assimilation Codes

DAO	p	PSAS interface layer with 2O0K observations/day
	q_c	CAM with finite volume dynamics at 2°x2.5°L55, including CLM
NCEP	r	Global atmospheric spectral model at T170L42
	s	SSI analysis system with 250K observations/day, 2 tracers
	t	WRF regional atmospheric model at 22km resolution CONUS forecast 345x569L50
NSIPP	u_c	ODAS with OI analysis system at 1.25°x1.25°L20 resolution with ~10K observations/day
MIT	v	MITgcm 2.8° century / millennium adjoint sensitivity

ESMF Interoperability Demonstrations

COUPLED CONFIGURATION	NEW SCIENCE ENABLED
GFDL B-grid atm / MITgcm ocn	Global biogeochemistry (CO2, O2), SI timescales.
GFDL MOM4 / NCEP forecast	NCEP seasonal forecasting system.
NSIPP ocean / LANL CICE	Sea ice model for extension of SI system to centennial time scales.
NSIPP atm / DAO analysis	Assimilated initial state for SI.
DAO analysis / NCEP model	Intercomparison of systems for NASA/NOAA joint center for satellite data assimilation.
DAO CAM-fv / NCEP analysis	Intercomparison of systems for NASA/NOAA joint center for satellite data assimilation.
NCAR CAM Eul / MITgcm ocn	Improved climate predictive capability: climate sensitivity to large component interchange, optimized initial conditions.
NCEP WRF / GFDL MOM4	Development of hurricane prediction capability.

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Design goals

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Component interoperability

Facilitate the exchange of software components among research centers and the reconfiguration of individual applications (e.g., multiple dynamical cores, active and data-only versions of a geophysical components)

Performance portability

Buffer the researcher against varied, transient computer platforms, while preserving computational efficiency

Ease of use

Provide an interface that uses terminology familiar to scientists, in F90

Software reuse

Include utility infrastructure that can be shared by many research groups

Ease of adoption

Minimize lines of source code that must be changed for framework adoption; accommodate multiple component execution models (sequential, concurrent, mixed)

Ease of scientific experimentation

Enable the user to easily initiate new component interactions

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Software Design Paradigm

- Object-oriented design
  - Encapsulation
  - Inheritance
  - Polymorphism
  - ESMF is being implemented in C++ and Fortran 90, so only basic OOP concepts can be implemented
- Component-based design
  - Applications are constructed by using software entities called *components* which are accessed only thru *interfaces* (e.g., COM, CORBA, CCA)
- Layered design

Implementation

- The Library includes C++ and F90 bindings
  - Utilities mostly written in C/C++
  - Fields/Grids written in F90
- *No direct access of Fortran derived types.* Elements of derived types are *private.*
- *All types must be explicitly initialized*
  - F90: `Create()/Init()` methods should be called before using a derived type

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Architecture

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ESMF SUPERSTRUCTURE
coupling services

gridded components,
coupling components,
custom components

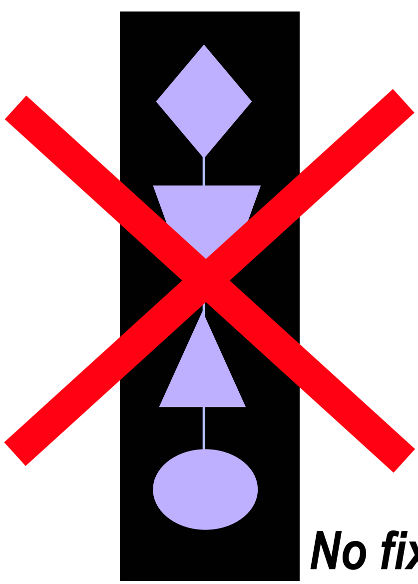
user-created model components

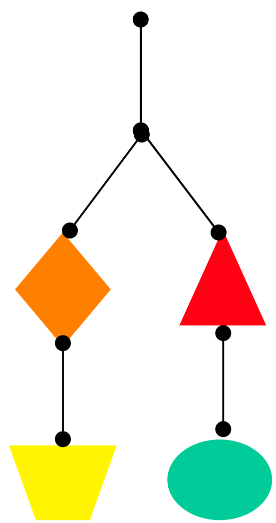
ESMF INFRASTRUCTURE
integrated system utilities

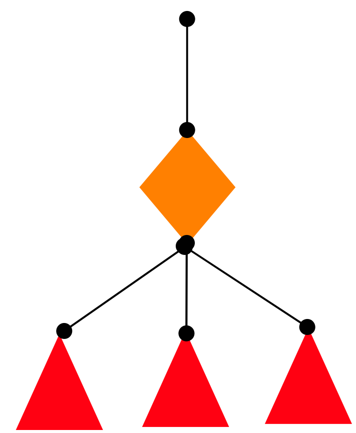
grids, transforms,
communication kernel,
timekeeping, …

Flexible configuration

The ESMF architecture defines components that can work in many configurations, not a single framework into which all components must fit.







No fixed template … instead, tools for assembling varied applications

Superstructure

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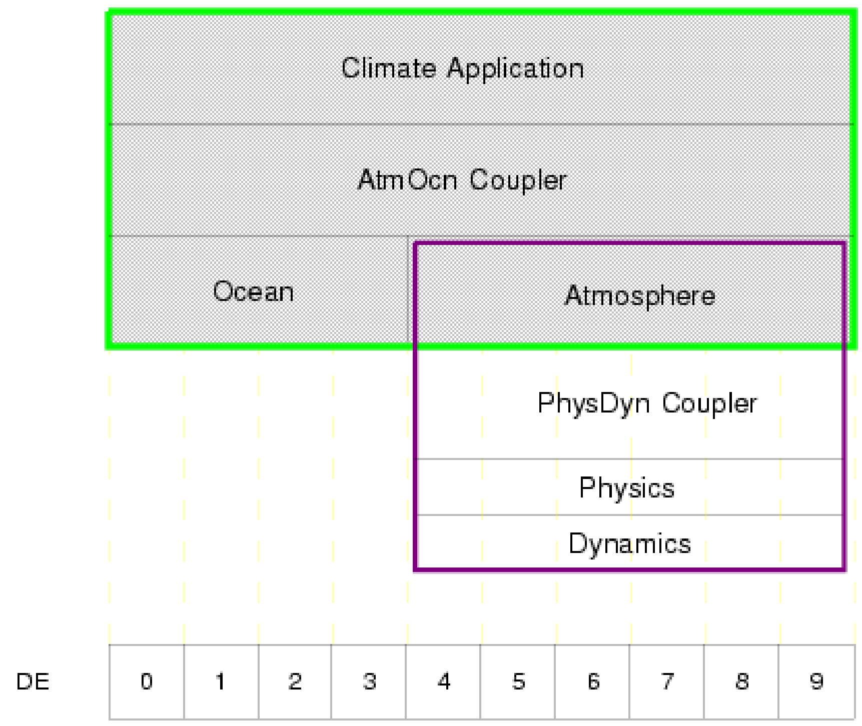
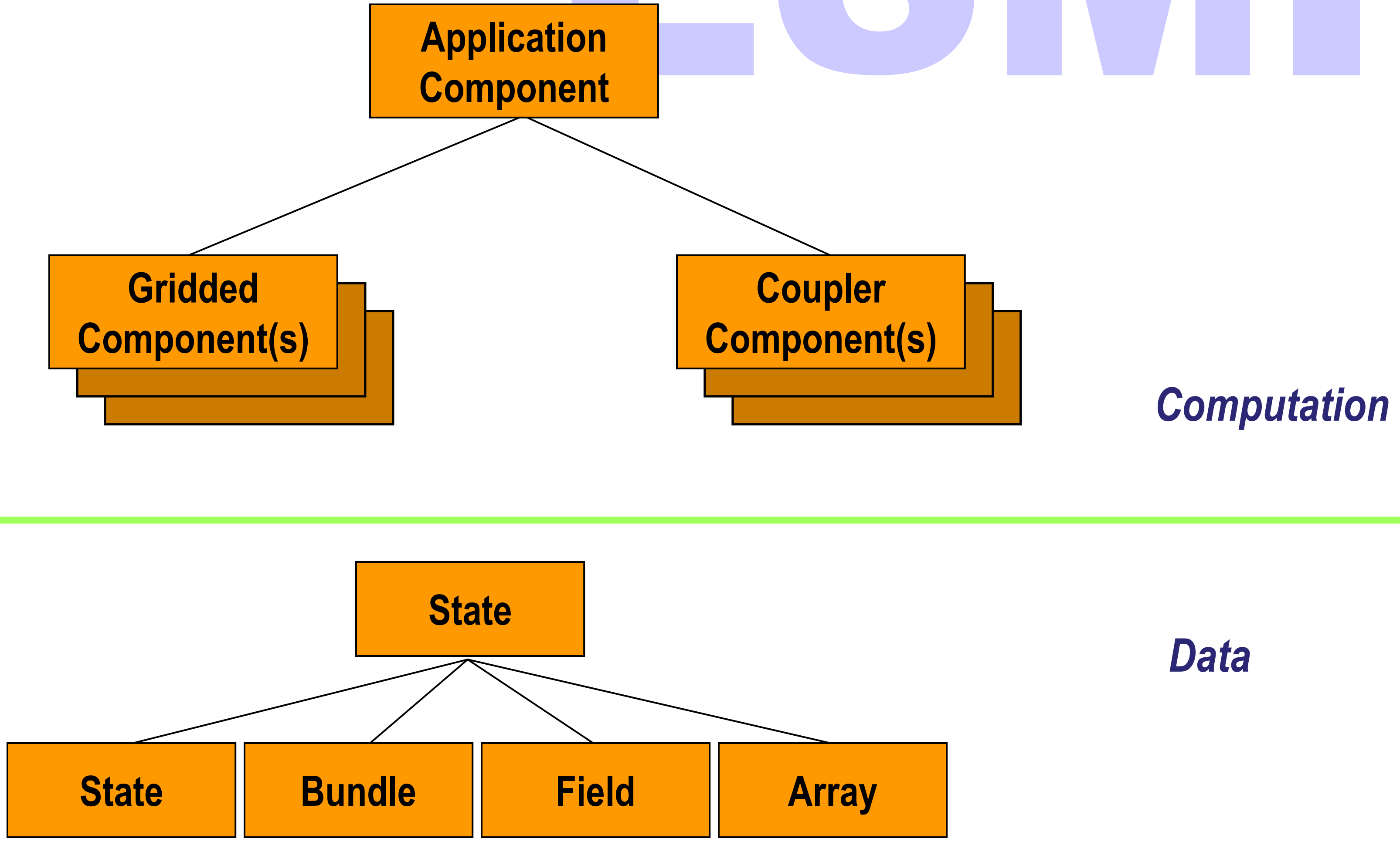
- Typically, a climate application will have
  - One application component
  - One or more gridded components
  - One or more couplers
- Gridded components may be nested
- Gridded components may run on same set of DEs, or not
- ESMF supports SPMD and MPMD
- ESMF does provide or require a *flux coupler*



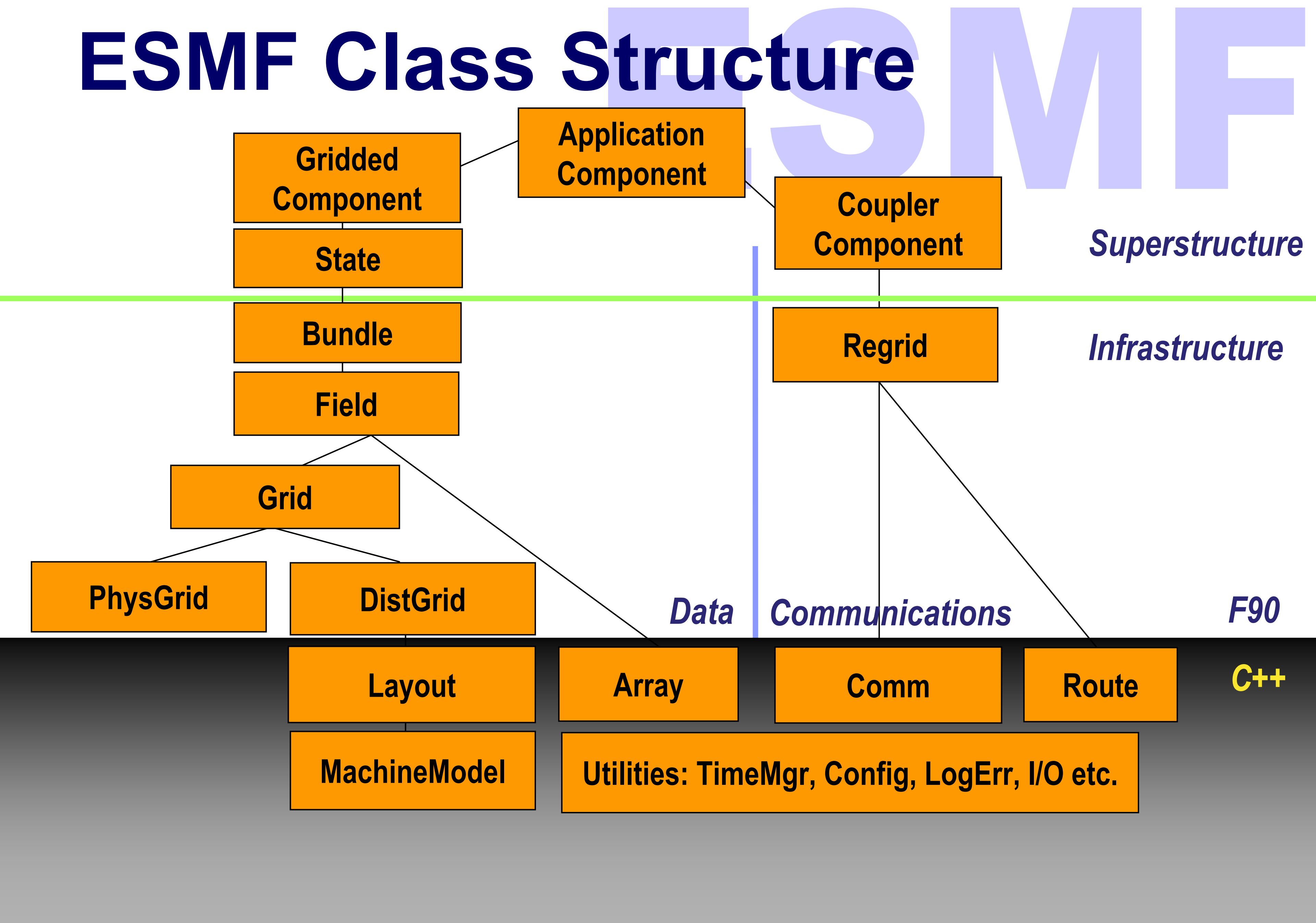
Superstructure Classes



Infrastructure: Utilities

- Base
- Attributes
- Machine Model
- PE List
- Layout
- Basic Communications
- Time Manager
- Registry
- Error Handling
- Logging
- Performance Profiling
- Configuration Attributes

ESMF Class Structure



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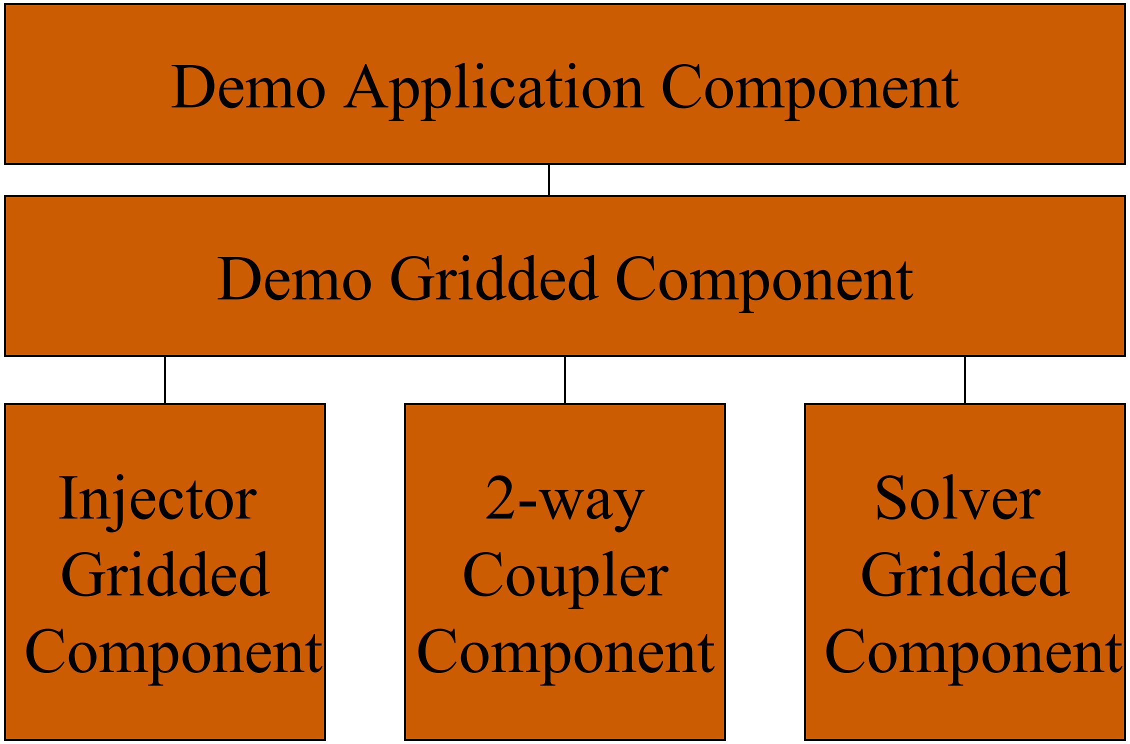
ESMF Demo Overview

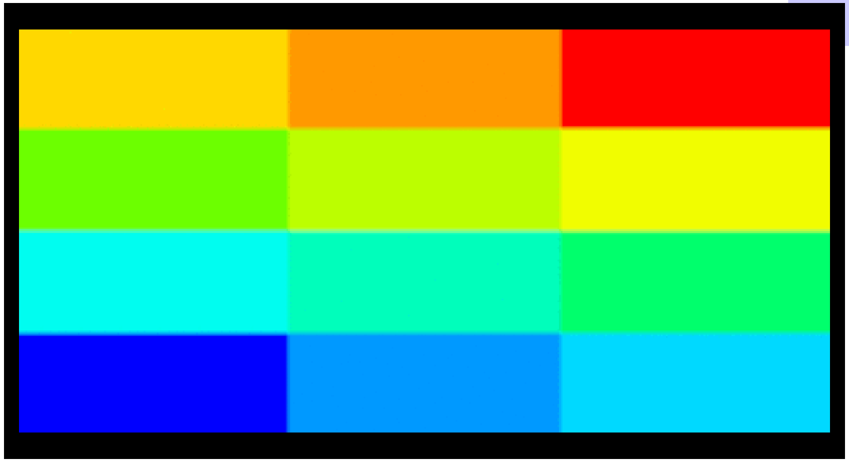
- One Component calculates compressible flow around obstacles, with energy equation (FlowSolverMod). Initial Flow is left to right over heated obstacles.
- Second component calculates injector properties (InjectorMod), coupled to FlowSolver.
- Similar to river run-off into an Ocean model.

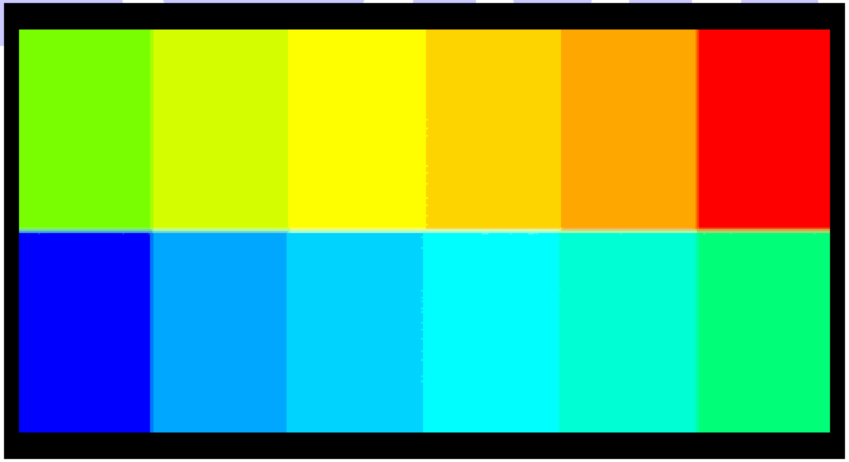
Demo Component Structure

All code in these files is user-written code, not part of the ESMF Framework.



Layouts in the Demo





- The demo runs 4, 8, 12 and 16-way. For the 12-way decomposition the Injector component decomposes the data in a 6x2 pattern, and the Solver uses 3x4. This is controlled by the type of Layout associated with each Component.

Demo Output Visualized

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

ESMF Adoption Curve: Incremental Path

- **Minimum:** Component interfaces/subroutines, Data in Fields, Time via Clocks, information exchange via States
- **Plus any or all of:** Time Mgr with Internal Clocks, Data in ESMF Fields/Grids, Regrid/Halo of Fields, Logging, Configuration files

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Summary

ESMF eliminates software barriers to collaboration among organizations

- Easy exchange of model components accelerates progress in NWP and climate modeling
- Independently developed models and data assimilation methods can be combined and tested
- Coupled model development becomes truly distributed process
- Advances from smaller academic groups easily adopted by large modeling centers

ESMF facilitates development of new interdisciplinary collaborations

- Simplifies extension of climate models to upper atmosphere
- Accelerates inclusion of advanced biogeochemical components into climate models
- Develops clear path for many other communities to use, improve, and extend climate models
- Many new model components gain easy access to the power of data assimilation